INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.142

The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing

A. Mallalieu ✉, T. Hajali, O. Isaksson and M. Panarotto
Chalmers University of Technology, Sweden
✉ adammal@chalmers.se

Abstract
The use of Additive Manufacturing (AM) can bring opportunities for industry, but several challenges need to be addressed, specifically the digital infrastructure comprising the AM value chain. A combination of a systematic literature review and an industrial use case study concludes that there is low consideration of the digital infrastructure in Design for Additive Manufacturing (DfAM) methods and tools which has a negative impact on the industrialisation of AM. It is therefore recommended that further studies are to be made on how to manage the digital infrastructure in DfAM processes.

Keywords: additive manufacturing, digital design, design tools, industrialisation

1. Introduction

This paper addresses the role of the digital infrastructure in Design for Additive Manufacturing (DfAM) and how it affects the industrialisation of additive manufacturing (AM). The digital infrastructure comprises the information technologies used together to process the vast amount of data that is being generated, transferred, stored, and traced in the AM process steps. By using AM, it is possible to print directly based on virtual 3D models which brings many opportunities such as lightweight- and freedom of design (Diegel et al., 2019). AM has been subject to intense research and development activities and is judged to be a critical technology for industrial competitiveness (AM-motion, 2016). The AM-motion roadmap further includes the data processing in a complex AM process in two of the top three priorities for the successful development of AM (see table 7.1 in AM-motion, 2016).

One critical phase in the AM process is the design phase, where DfAM is the collective term for methods, tools, and guides for an effective design dedicated for AM. DfAM seeks to utilize AM's opportunities while accounting for the many different process-specific constraints of AM (Diegel et al., 2019). Several DfAM methods and tools have been proposed which have resulted in different software, however, this has led to issues related to the digital infrastructure (Alfaify et al., 2020). The DfAM process is digital-intense, and the digital infrastructure requires consideration (Leary, 2020). One example is the coupling and integration between simulation models and software's in the DfAM process (Wiberg et al., 2019). A dominant standard for AM geometry representation is the STereoLithography (STL) (Kai et al., 1997), but since it is discrete and triangular it cannot represent the higher-order representations used by Computer Aided Design (CAD) systems. As such it can only communicate limited information and is practically a source to integration and coupling problems. More consideration needs to be put on how methods and tools are developed such that they can be used in conjunction with already existing digital infrastructure, which is important for adoption by industry (Gericke et al., 2020).

All together this makes it of interest to review how DfAM methods and tools consider the digital infrastructure and identify a potential gap in the literature. Furthermore, the paper also aims to explore how the digital infrastructure affects the industrialisation of AM. The following research questions can thus be formulated.

- *RQ1. In what way is the digital infrastructure considered in DfAM methods and tools*
- *RQ2. How does this impact the industrialisation of AM?*

The remainder of this paper addresses the research questions accordingly. First, the method used for investigation is presented. Second, a systematic literature review is conducted to investigate how the digital infrastructure is treated in literature. Third, an industrial use case study is performed which explores the digital infrastructure in a DfAM process identifying potential challenges. Finally, RQ1 and RQ2 are discussed in relation to the findings making it possible to make conclusions and future recommendations.

2. Method

This study combines a systematic literature review along with an industrial use case study, the results are then analysed in relation to each other. The two approaches are described in further detail below.

2.1. Systematic literature review

A systematic literature review is conducted to investigate how DfAM methods and tools consider the digital infrastructure to potentially identify a research gap. A systematic literature review is set up to find research gaps within a specific research topic (Wholin, 2014). It is also important to clarify what is meant by a DfAM-process, -method, and -tool. The following notions, in agreement with (Gericke et al., 2017) are used for the purpose of this paper:

A design process is "a formally specified sequence of activities to be carried out in developing a particular design";

A design method is "a specification of how a specified result is to be achieved";

A tool is "an object, artefact or software that is used to perform some action". These definitions are applied in the context of DfAM in this systematic literature review.

The **first step** in the systematic literature review was to search for literature using a keyword search SCOPUS. A few sets of keywords were tested to get a feasible number of articles to review. The final text string was set as: "((additive AND manufacturing) OR (3d AND printing) AND (digital OR data) AND design AND (tool OR method))". The aim of the systematic literature review is to investigate how the digital infrastructure is treated, thus justifying the inclusion of "digital", it was also noted through iterations that adding "data" was relevant addition as well since it resulted in additional literature. A total of 209 publications were collected in the first step. The **second step** the systematic literature review was used to screen the publication targets. Journals, conferences, and trade journals were used to limit the inclusion. The **third step** in the systematic literature review was to screen publications based on abstracts. This meant that publications that did not regard DfAM methods or tools or methods related to data or digital were removed. Examples of excluded publications were review publications or phenomena studies. Methods and tools not related to engineering design were also used excluded, methods and tools related to civil engineering applications were for example excluded. A total of 53 articles were reviewed. The **fourth step** in the systematic literature review was to review the remaining papers based on how the digital infrastructure was considered. An additional 9 publications were excluded because it became evident that they were not relevant first while reading the full text. The **final step** in the systematic literature review was to analyse how the 44 remaining articles considered the digital infrastructure and map potential patterns.

2.2. Industrial use case

The purpose of the industrial use case was to explore how the digital infrastructure impacts the industrialisation of AM in general, and DfAM in particular. The industrial use case is based on a Swedish manufacturer of construction equipment. The company seeks to investigate the potential of AM as an option to produce production tools used by operators on the assembly line. AM is particularly considered an interesting option since these production tools are often produced in low volume and are customised for operators. This would mean that AM could reduce the time and cost of the current design, procurement, or production of tools. There is also an expectation that AM can increase the usability of the tools by e.g., lightweight designs. The use case was analysed using a series of six one-hour semi-structured interviews, with 6 employees and managers directly involved in today's design and acquisition of production tools in the company, during a two-month period. The purpose of the interviews was to understand the current design process in order to define an appropriate DfAM process that could be used in the case study since there is no present DfAM process established within the company. The case study was conducted during a three-month period in parallel with the series of interviews, where two different tool designs were used as input to the case study. The case study results were later analysed in relation to the results from the systematic literature review to highlight the impact of the digital infrastructure.

3. Results

There are results from both the systematic literature and from the case study. This section begins to present the results from the systematic literature review. This is followed by the results from the case study along with how it impacts the industrialisation industrialization of AM.

3.1. Digital infrastructure of DfAM methods and tools

The systematic literature review made use of five different categories to highlight how the digital infrastructure is considered in DfAM methods and tools. These five categories are: (1) Data format incompatibility; (2) Information management; (3) Data analysis; (4) Loss of information;(5) Data and information reuse. Where the papers addressed issues in these categories is mapped in Table 1.

Table 1. Results of the systematic literature review for the five categories.

Articles	1	2	3	4	5	Articles	1	2	3	4	5
Mathias et al., 2008		x	x	x		Rezayat et al., 2019					
Song et al., 2009		x		x		He et al., 2019					x
Smith and Rennie, 2010		x				Adkins et al., 2020			x		
Huang and Eisenberg, 2012						Capunaman, 2020					
Chang and Chen, 2014	x	x				Rossing et al., 2020					
Tucker et al., 2014	x	x	x	x	x	Zhang et al., 2020					
Li-Jun et al., 2015		x		x		Rice et al., 2020					
Savage et al., 2015			x			Li et al., 2020					
Grimm et al., 2015	x			x		Noma et al., 2020					
Jalil et al., 2016						Gao et al., 2020					
Huang et al., 2016	x					Dagkolu et al., 2020					
Peng et al., 2016	x					Afazov et al., 2021			x		
Bader and Oxman, 2016						Olsen et al., 2021					
Egan et al., 2017						Marschall et al., 2021					
McMillan et al., 2017	x			x		Özen et al., 2021					x
Song et al., 2017						Askari et al., 2021					
Anand et al., 2018	x	x		x		Reid et al., 2021					
Bender and Barari, 2019	x			x		Balamurugan and Selvakumar, 2021					
Garcia et al., 2019			x			Mustafa and Lazoglu, 2021	x	x		x	
Lerebours et al., 2019	x					Srinivasan et al., 2021					
Valainis et al., 2019	x					Ren et al., 2021					
Babcinschi et al., 2019	x	x	x	x		Huang et al., 2021					

These categories are further presented in the subsections below, aiming to provide more detail in how they were considered in the reviewed literature.

https://doi.org/10.1017/pds.2022.142 Published online by Cambridge University Press

3.1.1. Data format incompatibility

Individual DfAM methods and tools typically make use of different software, and any software has its specific data format. This can make the DfAM process complex, and it can be troublesome to not consider the compatibility between different data formats and the integration between different tools (McMillan et al, 2017). A large variety of data formats can also have a negative effect on the interoperability in the AM workflow (Babcinschi et al., 2019). Chang and Chen (2014) address the specific challenge of transferring text strings generated by knowledge-based systems into a CAD software. Bender and Barari (2019) mentions the importance of format compatibility and uses the example of topology optimization, since the output from the topology optimization must be compatible with the input to the AM system. Grimm et al. (2015) state that AM tends to fall short in terms of format incompatibility due to issues with integration between systems and software. They continue to propose the Jupiter Tessellation (JT) format as a potential format to use in order to overcome some of the incompatibility issues. 12 of the authors either considered the format being used in their own specific DfAM method or tool or problematised it. This is visualised in the first category in Table 1. It should also be mentioned that there were no authors, except for Chang and Chen (2014) and Grimm et al. (2015), who addressed how their data format can be compatible with other methods or tools, or how the output can be used in downstream activities in the DfAM process.

3.1.2. Information management

In this paper, 'information management' is interpreted as the activity to manage information including transferring, storing, tracing, and retrieving information, and contrast to information processing activities, where information content is modified. Tucker et al. (2014) developed a solution that can capture the geometry of a physical object through scanning. The data is translated into an STL format and gets stored in a cloud-based service. Tucker et al. (2014) also highlight several digital challenges such as information loss, and opportunities such as reuse of knowledge and data. Li-Jun et al. (2015) address the issue of storing large print files and propose a method to compress data. The proposed method also considers the tracing of data and explicitly describes how to generate file IDs during the compression of data. Babsinschi et al. (2019) state that the traditional methodology for data exchange is done manually consisting of heterogeneous data formats which makes the process impractical and time-consuming. The implication of information management in DfAM methods and tools was only considered in nine of the reviewed articles, as seen by the second category in Table 1.

3.1.3. Data analysis

Data analysis is described as the set of activities to understand and interpret data to gain insight and knowledge of AM processes. This includes also the 'cleaning' of data in advance of analysis, typically a time-requiring process. Data processing is mentioned by Savage et al. (2015) who propose a scanning method to capture geometries but emphasise that expertise is required to clean the meshes in order to make use of the data. Another scanning method to capture geometries is proposed by Mathias et al. (2008) who highlights the need to process or clean data before using it, while also adding the potential implication of losing information in the cleaning process. The need of cleaning or processing the data generated by DfAM methods and tools were seemingly neglected and was only mentioned by seven authors in the reviewed literature, as illustrated by the third category in Table 1.

3.1.4. Loss of information

The loss of information in the AM workflow specifically relates to the potential loss of information that can occur either when using a specific tool or method, or when transferring in-between two methods or tools. There were several examples of these highlighted in the reviewed literature. Tucker et al. (2014) state that it can happen when the geometry is captured through scanning and represented as mesh. This happens since the scanner's resolution affects the generated mesh, which potentially can lead to the loss of geometrical features. Some scanners also fail to capture internal structures and typically require cleaning (Mathias et al., 2008), which are another two sources for loss of information. Grimm et al. (2015) also mention that exporting CAD-formats to STL-format cut modelling knowledge such as

https://doi.org/10.1017/pds.2022.142 Published online by Cambridge University Press

design features, parameters, and modelling history. The export process also approximates exact shapes in the tessellation. The issue of STL is also addressed by both Bender and Barari (2019) and McMillan et al. (2017) who specifically state that the STL does not consist of appropriate or enough information to be of effective use for AM and propose an alternative solution in direct slicing of finite element mesh. Song et al. (2009) developed a geometrical design tool in the form of a pencil that can capture the movement of a hand and create a digital representation, where much effort was put into the ability to capture the movement correctly and create an appropriate digital representation of the intended design. Li-Jun et al. (2015) proposed a method to compress print file data and clearly stated that the method does not result in loss of information. The implication of loss of information either, by a single or in-between, DfAM methods and tools was considered ten times in the reviewed literature, as seen by the fourth category in Table 1.

3.1.5. Data and information reuse

Data and information reuse is to some extent related to information management since it requires the ability to trace and transfer data. This category is more seen as an opportunity and refers to the knowledge that can be captured and exploited from the data and information that is generated by DfAM methods and tools. Tucker et al. (2014) exemplify this when he proposes a method that enables the capturing and reuse of design knowledge more accessible through a set of hardware and software. Özen et al. (2021) developed a machine learning approach to make use of data to calculate porosity. Only three authors considered the opportunity to reuse the data and information generated by DfAM methods and tools, as seen in the fifth category in Table 1.

3.2. Results from the use case study

The purpose of the case study was to investigate potential challenges related to the digital infrastructure of a DfAM process and its potential impact on the industrialisation of AM. This section presents the case study which clarifies more practically what comprises the digital infrastructure. This is followed by analysing its potential impact on the industrialisation of AM.

3.2.1. Case study implementation

The case study consisted of performing a sequence of defined activities adapted to fit the current in-house tool design process and AM. The intended goal of the DfAM process from the case company perspective was to minimize the weight of the current designs while being cost- and time-efficient from both a process and design perspective.

Performing the sequence of activities in the DfAM process resulted in a digital infrastructure, and this is visualised in Figure 1. The digital infrastructure is comprised of; the methods, tools, and software used; the data formats for the inputs and outputs; the flow of data or information. Three different software were used: Fusion 360 to perform a generative design, more specifically topology optimization, to minimize weight; CAD Catia V5 to change the geometry of the original CAD file and to perform a simple FEM analysis on the proposed designs; Markforged webservice was mainly used to prepare the print, and is a specific software used for Markforged two composite FDM printer. This software can also provide print data such as cost, time to print, and volume of used material. Each activity consists of both inputs as well as outputs, and both respectively have their individual data formats. Catia V5 can for example make use of STL, Standard for The Exchange of Product Data (STEP), or its own CAD-file format as input and output. Markforged webservice makes use of STL as input and its output is its own print file format. Fusion 360 had STP as input for CAD files, and the requirements and 2D drawings as Portable Document Format (PDF) which were interpreted and inserted into the software. The output of Fusion 360 is STL. Three of the visualized activities were performed by design engineers, with experience in CAD Catia V5 and Fusion 360. The print preparation was performed by an AM engineer with experience from printing with Markforged two printers.

https://doi.org/10.1017/pds.2022.142 Published online by Cambridge University Press

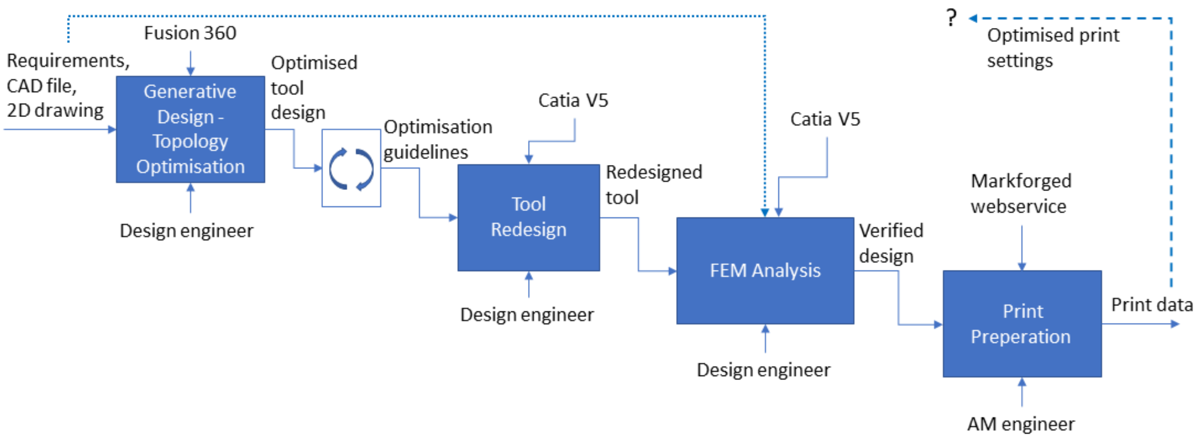

Figure 1. Set of performed activities in the case study and its corresponding digital infrastructure

3.2.2. Impact of the digital infrastructure on the industrialisation of AM

Several challenges or potential issues related to the digital infrastructure were observed in the case study. These challenges are presented according to the categories used in the systematic literature review. The issue of **data format incompatibility** was observed in the case study and is highlighted by the transformative step in Figure 1. The output format from *F*usion 360 is STL, and this format cannot be used to change the geometry using CAD software. The output of the generative design, therefore, had to be manually implemented on the original CAD file. Furthermore, the requirements and 2D drawings were used as input to define boundary conditions, constraints, and optimisation targets in the generative design. The format of the 2D drawings and requirements were PDFs, and therefore had to be interpreted by the design engineer and implemented manually in the generative design software. The use of formats and consideration of output/input compatibility is relevant for DfAM methods and tools to function in conjunction. Mainly since poor consideration in the case study resulted in a less effective and efficient DfAM process. Consideration of **information management** was deemed as important in the case study. The case study produced a large amount of data and information which both needed to be stored, communicated, and traced between different activities. An example of this was the requirements needed in the FEM analysis, which is illustrated by the dotted line in Figure 1. Moreover, the results from the FEM analysis used to verify the design had to be stored for future purposes. The Markforged webservice also generated print data that needed to be linked to the individual tools. **Data analysis** was needed in the case study since some of the generated data or information had to be processed before entering the next step. The output from the generative design was not only delivered in a non-compatible format but did also require manual cleaning to ensure that the proposed design could be printed. The print data also had to be sorted such that it was possible to analyse the cost and time for the proposed designs. This was considered as time-consuming. **Loss of information** was observed on two occasions in the case study. Firstly, requirements were used as input to the generative design. The requirements were interpreted incorrectly in early iterations which generated a set of unfeasible designs, this was a result of information loss between these two steps. Secondly, as indicated in the transformative step, the optimised design had to be translated into general guidelines for the design. This resulted in information loss since some aspects of the optimised geometry were not possible to replicate. There were some identified possibilities for **data and information reuse** in the case study. An example of this was the produced print data, illustrated in the dashed line in Figure 1. It was possible to make use of it to find ways of optimising the print settings, and this could potentially be reused for future prints. There was also an expressed desire by the industrial experts to make use of the generated data and information to create and capture knowledge. It was however unclear how it can be extracted and used efficiently.

To summarize, the observed issues seemingly influenced the DfAM process making it less effective and efficient. The goal of the case study was to make the tools more lightweight, and this was limited by the digital infrastructure, thus making the DfAM process ineffective. An additional goal was to make the design and process time- and cost-efficient. This was also limited by the digital infrastructure, thus

https://doi.org/10.1017/pds.2022.142 Published online by Cambridge University Press

making the DfAM process inefficient. This could potentially have a negative effect on the industrialisation of AM, which is further discussed below.

4. Discussion

The systematic review made use of five categories were used to analyse how the literature considers the digital infrastructure, and this was presented in Table 1. It appears to be low consideration of the five categories while also being scattered among the literature, and this indicates that there is seemingly a research gap related to how it is treated in literature. In addition to this, the case study explored the digital infrastructure's potential impact on the industrialisation of AM. The case study made it evident that the digital infrastructure can have negative effects and make the DfAM process both ineffective and inefficient.

Ineffective in the sense that the results from methods and tools can be non-utilised. This happened in the case study where the output had to be manually inserted thus losing certain aspects of the optimised lightweight design. The early iterations of the optimised design were also non-feasible as a result of interpreting the requirements inaccurately in Fusion 360. This will in turn limit the ability to exploit the opportunities that AM brings, such as lightweight designs. There was also a possibility to make use of the optimised print settings for future use which highlights a potential opportunity.

The DfAM process can also become **inefficient** and there were three concrete examples of this in the cast study. Firstly, there was time wasted on early iterations in the generative design also a result of interpreting the requirements inaccurately. Secondly, there was also time wasted on manually implementing the output from the generative design along with processing the specific results. Thirdly, it was unclear where and how the generated data were to be used or even reused, such as the FEM results, the requirements, as well as the optimised print settings and data. This will in turn limit the ability to exploit the opportunities that AM bring, such as reduced time to market. Following the insights from this literature study in combination with the industrial use case, we argue that DfAM needs better to account for its interaction with the digital infrastructure, to succeed in industrialisation of AM. Specifically, what output a method or tool generates along with where and how it can be used downstream in the DfAM process and throughout the AM lifecycle (Mies et al., 2016). At the same time, there needs to be consideration of what and how the required input is obtained from upstream activities. Finally, we would also argue that the digital infrastructure needs to be studied further. Additional use cases need to be studied along with more extensive and in-depth cases with industrial partners.

5. Conclusion

The aim of this paper was to investigate how DfAM methods and tools consider the digital infrastructure, in order to identify a potential research gap. Furthermore, also explore how it affects the industrialisation of AM. A systematic literature review was used to frame how the digital infrastructure is considered which highlighted that there is a low consideration of the digital infrastructure in current DfAM methods and tools. It can therefore be concluded that there is a low consideration in DfAM methods and tools, which indicates a research gap regarding the digital infrastructure. An industrial use case study was then used to explore the potential impact this can have on the industrialisation of AM. The initial industrial case study indicates that the way that data and information are processed and managed influences the industrialisation of AM negatively. Mainly since extra effort and time is spent on non-value adding activities, where the data produced and analysed in AM need to be treated already in the DfAM activities to make use of AM's full potential. It is therefore recommended that further studies are to be made on how to manage the digital infrastructure in DfAM processes.

Acknowledgements

This study was financially supported by the Department of Industrial and Materials Science at Chalmers University of Technology in collaboration with the VINNOVA funded project Demonstration of Infrastructure for Digitalization enabling industrialization of Additive Manufacturing (DiDAM). The authors wish to thank the industrial case company for participating in interviews as well as providing two cases for the industrial use case study.

https://doi.org/10.1017/pds.2022.142 Published online by Cambridge University Press

References

Adkins, G., Little, C., Meyerhofer, P., Flynn, G. and Hammond, K. (2020), "Characterizing dynamics of additively manufactured parts", *Conference Proceedings of the Society for Experimental Mechanics Series*, Vol. 8, pp. 171–183. https://doi.org/10.1007/978-3-030-12684-1_17

Afazov, S., Semerdzhieva, E., Scrimieri, D., Serjouei, A., Kairoshev, B. and Derguti, F. (2021), "An improved distortion compensation approach for additive manufacturing using optically scanned data", *Virtual and Physical Prototyping*, Taylor & Francis, Vol. 16 No. 1, pp. 1–13. https://doi.org/10.1080/17452759.2021.1881702

Alfaify, A., Saleh, M., Abdullah, F.M. and Al-Ahmari, A.M. (2020), "Design for additive manufacturing: A systematic review", *Sustainability*, Vol. 12 No. 19. https://doi.org/10.3390/SU12197936

AM-motion (2016), A strategic approach to increasing Europe's value proposition for additive manufacturing technologies and capabilities, European Commission. Available at: https://cordis.europa.eu/project/id/723560/results [Last Accessed: 22 February 2022]

Anand, S., Ghalsasi, O., Zhang, B., Goel, A., Reddy, S., Joshi, S. and Morris, G. (2018), "Additive Manufacturing Simulation Tools in Education," 2018 *World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC)*, 2018, pp. 1-6. 10.1109/WEEF-GEDC.2018.8629689

Askari, G.H., Dar, U.A., Abid, M., Nutkani, M.B., Pasha, R.A. and Jamil, A. (2021), "Energy absorption and compression behaviour of polymeric 3D printed lattice structures - Experimental and numerical study", *Proceedings of 18th International Bhurban Conference on Applied Sciences and Technologies*, IBCAST 2021, pp. 198–203. https://doi.org/10.1109/IBCAST51254.2021.9393216

Babcinschi, M., Freire, B., Neto, P., Ferreira, L.A., Señaris, B.L. and Vidal, F. (2019), "AutomationML for Data Exchange in the Robotic Process of Metal Additive Manufacturing", *IEEE International Conference on Emerging Technologies and Factory Automation (EFTA)*, ETFA, pp. 65–70. https://doi.org/10.1109/ETFA.2019.8869079

Bader, C. and Oxman, N. (2016), "Recursive symmetries for geometrically complex and materially heterogeneous additive manufacturing", *Computer-Aided Design*, Vol. 81, pp. 39–47. https://doi.org/10.1016/j.cad.2016.09.002

Balamurugan, P. and Selvakumar, N. (2021), "Development of patient specific dental implant using 3D printing", *Journal of Ambient Intelligence and Humanized Computing*, Springer Berlin Heidelberg, Vol. 12 No. 3, pp. 3549–3558. https://doi.org/10.1007/s12652-020-02758-6

Bender, D. and Barari, A. (2019), "Direct solid element slicing in topology optimization for additive manufacturing", *Proceedings of the ASME Design Engineering Technical Conference*, Vol. 1 No. viii, pp. 1–6. https://doi.org/10.1115/DETC2019-98452

Capunaman, O.B. (2020), "CAM as a Tool for Creative Expression-Informing Digital Fabrication through Human Interaction.", *25th International Conference on Computer-Aided Architectural Design Research*, Vol. 1, pp. 243–252.

Chang, D. and Chen, C.H. (2014), "Integration of knowledge engineering and 3d printing for digital design and manufacturing - A case study", *Proceedings of the International Conference on Progress in Additive Manufacturing*, Vol. 0, pp. 47–52. https://doi.org/10.3850/978-981-09-0446-3_060

Dagkolu, A., Gokdag, I. and Yilmaz, O. (2020), "Design and additive manufacturing of a fatigue-critical aerospace part using topology optimization and L-PBF process", *Procedia Manufacturing*, Vol. 54, pp. 238–243. https://doi.org/10.1016/j.promfg.2021.07.037

Diegel, O., Nordin, A. and Motte, D. (2019), *A Practical Guide to Design for Additive Manufacturing*, Springer Series in Advanced Manufacturing. Singapore.

Egan, P.F., Engensperger, M., Ferguson, S.J. and Shea, K. (2017), "Design and Fabrication of 3D Printed Tissue Scaffolds Informed by Mechanics and Fluids Simulations", *Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 2A.* Cleveland, Ohio, USA, August 6–9, 2017. https://doi.org/10.1115/DETC2017-67602

Gao, Z., Li, D., Dong, G. and Zhao, Y.F. (2020a), "Crack path-engineered 2D octet-truss lattice with bio-inspired crack deflection", *Additive Manufacturing*, Vol. 36. https://doi.org/10.1016/j.addma.2020.101539

Garcia, D., Wu, Z., Kim, J.Y., Yu, H.Z. and Zhu, Y. (2019), "Heterogeneous materials design in additive manufacturing: Model calibration and uncertainty-guided model selection", *Additive Manufacturing*, Vol. 27, pp. 61–71. https://doi.org/10.1016/j.addma.2019.02.014

Gericke, Kilian., Eckert, Claudia. and Stacey, Martin (2017). "What do we need to say about a design method?", *Proceedings 21st International Conference on Engineering Design*, Vancouver, Canada. 21-25 Aug 2017.

Gericke, K., Eckert, C., Campean, F., Clarkson, P.J., Flening, E., Isaksson, O., Kipouros, T., et al. (2020), "Supporting designers: Moving from method menagerie to method ecosystem", *Design Science*, pp. 1–22. https://doi.org/10.1017/dsj.2020.21

Grimm, M., Christ, A. and Anderl, R. (2015), “Distributed additive manufacturing-concept for the application of JT (ISO 14306) as downstream process format”, *Proceedings of the ASME Design Engineering Technical Conference*, Vol. 4, pp. 1–9. https://doi.org/10.1115/DETC2015-47418

He, L., Peng, H., Lin, M., Konjeti, R., Guimbretière, F. and Froehlich, J.E. (2019), “Ondulé: Designing and controlling 3D printable springs”, *UIST 2019: Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pp. 739–750. https://doi.org/10.1145/3332165.3347951

Huang, P., Li, Y., Chen, Y. and Zeng, J. (2016), “A Digital Material Design Framework for 3D-Printed Heterogeneous Objects”, *Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 1A*, Charlotte, North Carolina, USA. August 21–24, 2016. https://doi.org/10.1115/DETC2016-60181

Huang, S., Deng, X. and Lam, L.K. (2021), “Integrated design framework of 3D printed planar stainless tubular joint: Modelling, optimization, manufacturing, and experiment”, *Thin-Walled Structures*, Vol. 169. https://doi.org/10.1016/j.tws.2021.108463

Huang, Y. and Eisenberg, M. (2012), “Easigami: Virtual creation by physical folding”, *Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction*, TEI 2012, pp. 41–48. https://doi.org/10.1145/2148131.2148143

Jalil, S.B.A., Chou, S.M. and Tai, K. (2016), “Controlling polymer digital material composition with layering”, *Proceedings of the International Conference on Progress in Additive Manufacturing*, pp. 525–530. https://hdl.handle.net/10356/84340

Leary, M. (2020), " Chapter 3: Digital design for AM", *Design for Additive Manufacturing*, *Elsevier*, pp. 33-90. https://doi.org/10.1016/b978-0-12-816721-2.00003-8

Lerebours, A., Marin, F., Bouvier, S., Egles, C., Masquelet, A.C. and Rassineux, A. (2019), “A voxel-based method for designing a numerical biomechanical model patient-specific with an anatomical functional approach adapted to additive manufacturing”, *Computer Methods in Biomechanics and Biomedical Engineering*, Vol. 22 No. 3, pp. 304–312. https://doi.org/10.1080/10255842.2018.1552684

Li-Jun, X., Jun, G. and Wei-Yu, Z. (2015), “Compression research of bitmap data in three-dimensional printing”, *Open Mechanical Engineering Journal*, Vol. 9 No. 1, pp. 646–652. https://doi.org/10.2174/1874155X01509010646

Li, C.H., Wu, C.H. and Lin, C.L. (2020b), “Design of a patient-specific mandible reconstruction implant with dental prosthesis for metal 3D printing using integrated weighted topology optimization and finite element analysis”, *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 105. https://doi.org/10.1016/j.jmbbm.2020.103700

Kai, C. C., Jacob, G. G., & Mei, T. (1997), "Interface between CAD and rapid prototyping systems. Part 1: a study of existing interfaces", *The International Journal of Advanced Manufacturing Technology*, pp. 566-570.

Marschall, D., Sindinger, S.L., Rippl, H., Bartosova, M. and Schagerl, M. (2021), “Design, simulation, testing and application of laser-sintered conformal lattice structures on component level”, *Rapid Prototyping Journal*, Vol. 27 No. 11, pp. 43–57. https://doi.org/10.1108/RPJ-10-2020-0232

Mathias, M., Velay, X. and Wade, R. (2008), “The challenges of assessing digital product design”, DS 46: *Proceedings of E and PDE 2008, the 10th International Conference on Engineering and Product Design Education*, Barcelona, Spain, 2008.

McMillan, M.L., Jurg, M., Leary, M. and Brandt, M. (2017), “Programmatic generation of computationally efficient lattice structures for additive manufacture”, *Rapid Prototyping Journal*, Vol. 23 No. 3, pp. 486–494. https://doi.org/10.1108/RPJ-01-2016-0014

Mies, D., Marsden, W. and Warde, S. (2016), "Overview of Additive Manufacturing Informatics: “A Digital Thread”". *Integrating Materials and Manufacturing Innovation*, pp. 114–142. https://doi.org/10.1186/s40192-016-0050-7

Mustafa, S.S. and Lazoglu, I. (2021), “A new model and direct slicer for lattice structures”, *Structural and Multidisciplinary Optimization*, Vol. 63 No. 5, pp. 2211–2230. https://doi.org/10.1007/s00158-020-02796-w

Noma, Y., Narumi, K., Okuya, F. and Kawahara, Y. (2020), “Pop-up print: Rapidly 3D printing mechanically reversible objects in the folded state”, *UIST 2020 - Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pp. 58–70. https://doi.org/10.1145/3379337.3415853

Olsen, J., Day, S., Dupan, S., Nazarpour, K. and Dyson, M. (2021), “3D-Printing and Upper-Limb Prosthetic Sockets: Promises and Pitfalls”, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 29, pp. 527–535. 10.1109/TNSRE.2021.3057984

Peng, H., Wu, R., Marschner, S. and Guimbretière, F. (2016), “On-the-fly print: Incremental printing while modeling”, *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 887–896. https://doi.org/10.1145/2858036.2858106

Reid, A., Jackson, J.C. and Windmill, J.F.C. (2021), “Voxel based method for predictive modelling of solidification and stress in digital light processing based additive manufacture”, *Soft Matter*, Vol. 17 No. 7, pp. 1881–1887. https://doi.org/10.1039/D0SM01968B

Ren, Z., Xie, H. and Ju, Y. (2021), "Determination of the stress and strain fields in porous structures by photoelasticity and digital image correlation techniques", *Polymer Testing*, Vol. 102. https://doi.org/10.1016/j.polymertesting.2021.107315

Rezayat, H., Bell, J.R., Plotkowski, A.J. and Babu, S.S. (2019), "Multi-solution nature of topology optimization and its application in design for additive manufacturing", *Rapid Prototyping Journal*, Vol. 25 No. 9, pp. 1475–1481. https://doi.org/10.1108/RPJ-01-2018-0009

Rice, H.J., Kennedy, J., Göransson, P., Dowling, L. and Trimble, D. (2020), "Design of a Kelvin cell acoustic metamaterial", *Journal of Sound and Vibration*, Vol. 472. https://doi.org/10.1016/j.jsv.2019.115167

Rossing, L., Scharff, R.B.N., Chömpff, B., Wang, C.C.L. and Doubrovski, E.L. (2020), "Bonding between silicones and thermoplastics using 3D printed mechanical interlocking", *Materials and Design*, Vol. 186. https://doi.org/10.1016/j.matdes.2019.108254

Savage, V., Follmer, S., Li, J. and Hartmann, B. (2015), "Makers' marks: Physical markup for designing and fabricating functional objects", *UIST 2015 - Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*, pp. 103–108. https://doi.org/10.1145/2807442.2807508

Smith, P. and Rennie, A. (2010), "Computer aided material selection for additive manufacturing materials", *Virtual and Physical Prototyping*, Vol. 5 No. 4, pp. 209–213. https://doi.org/10.1080/17452759.2010.527556

Song, B., Feng, J. and Zhou, B. (2017), "Computational Design and fabrication of hanging structures", *SIGGRAPH Asia 2017 Technical Briefs*, SA 2017. https://doi.org/10.1145/3145749.3149429

Song, H., Guimbretière, F. and Lipson, H. (2009), "The ModelCraft framework: Capturing freehand annotations and edits to facilitate the 3D model design process using a digital pen", *ACM Transactions on Computer-Human Interaction*, Vol. 16 No. 3. https://doi.org/10.1145/1592440.1592443

Srinivasan, N.R., Chamala Vaishnavi, J., Varun Darshan, B.L., Srajaysikhar, D., Sakthivel, G. and Raghukiran, N. (2021), "Enhancement of an electric drill body using design for additive manufacturing", *Journal of Physics: Conference Series*, Vol. 1969 No. 1, pp. 0–11. 10.1088/1742-6596/1969/1/012025

Tucker, C.S., Saint John, D.B., Behoora, I. and Marcireau, A. (2014), "Open Source 3D Scanning and Printing for Design Capture and Realization", *Proceedings of the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 1B. Buffalo, New York, USA. August 17–20, 2014. https://doi.org/10.1115/detc2014-34801

Valainis, D., Dondl, P., Foehr, P., Burgkart, R., Kalkhof, S., Duda, G.N., Van Griensven, M., et al. (2019), "Integrated additive design and manufacturing approach for the bioengineering of bone scaffolds for favorable mechanical and biological properties", *Biomedical Materials*, Vol. 14 No. 6. https://doi.org/10.1088/1748-605X/ab38c6

Wiberg, A., Persson, J. and Ölvander, J. (2019), "Design for additive manufacturing – a review of available design methods and software", *Rapid Prototyping Journal*, Vol. 25 No. 6, pp. 1080–1094. https://doi.org/10.1108/RPJ-10-2018-0262

Wohlin, C. (2014), "Guidelines for snowballing in systematic literature studies and a replication in software engineering", *In Proceedings of the 18th international conference on evaluation and assessment in software engineering*, UK, ACM, New York, USA. pp. 1-10. https://doi.org/10.1145/2601248.2601268

Zhang, X.Y., Yan, X.C., Fang, G. and Liu, M. (2020), "Biomechanical influence of structural variation strategies on functionally graded scaffolds constructed with triply periodic minimal surface", *Additive Manufacturing*, Vol. 32. https://doi.org/10.1016/j.addma.2019.101015

Özen, A., Abali, B.E., Völlmecke, C., Gerstel, J. and Auhl, D. (2021), "Exploring the Role of Manufacturing Parameters on Microstructure and Mechanical Properties in Fused Deposition Modeling (FDM) Using PETG", *Applied Composite Materials*, Springer Netherlands, No. 0123456789. https://doi.org/10.1007/s10443-021-09940-9